Geometry, Parameter Estimation and Orbit Modeling for Hybrid Bistatic Missions

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Preface

This dissertation was written during my research work at the Center for Sensorsystems (ZESS), Project Sector 2 „Optimal Signal Processing - Data Fusion, Remote Sensing – SAR“ at the University of Siegen in Germany and later at the Research Establishment for Applied Science (FGAN), Research Institute for High Frequency Physics and Radar Techniques (FHR), Department for Array-based Radar Imaging (ARB) in Wachtberg, Germany.

I would like to take the opportunity to gratefully mention those persons who gave me advice and a great amount of support during my work.

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Abstract

The airborne / space borne hybrid bistatic radar experiment (TerraPAMIR) is planned to be carried out in 2008 involving the TerraSAR-X satellite as transmitter and the PAMIR system as receiver. The latter is an airborne SAR system that was constructed at FGAN (Forschungsgesellschaft für Angewandte Naturwissenschaften) [EN02]. Apart from the bistatic SAR processing, one of the main challenges is the geometrical synchronization of the antenna footprints. This work shows a way to set up the geometry of the experiment under realistic conditions, involving the earth rotation, an ellipsoidal orbit and the ellipsoidal shape of the WGS84 geoid. Some important parameters are derived, such as the antenna steering angle rate that is needed to synchronize the footprints of transmitter and receiver, the azimuth scene extension and the Doppler centroid that appears in the data. The azimuth antenna steering angles are most simply calculated using flat earth geometry. To make this possible, several effects on the transmitter's azimuth footprint velocity due to earth rotation and the ellipsoidal shape of the earth are compensated.

In the second part, this work also shows a possibility to track and interpolate gravitationally perturbated orbits using a Kalman filter algorithm. Position and / or velocity measurements are fused with information from a gravitation model to increase the accuracy of the resulting orbit trajectory.

Kurzfassung

Für das Jahr 2008 ist ein bistatisches hybrides SAR-Experiment in Planung (TerraPAMIR), bei dem ein orbitgestütztes Radarsystem (TerraSAR-X) als Sender und ein luftgetragenes System (PAMIR) als Empfänger kombiniert werden. Das PAMIR System wurde von der Forschungsgesellschaft für Angewandte Naturwissenschaften (FGAN) entwickelt [EN02]. Hier ist neben der Prozessierung der aufgenommenen Daten auch die geometrische Synchronisierung eine große Herausforderung. Diese Dissertation beschäftigt sich mit der Simulation der Geometrie unter realistischen Bedingungen. Sowohl die Erddrehung als auch die ellipsoide Form der Erde (WGS84) und des Orbits werden hier berücksichtigt. Daraus werden einige wichtige Parameter hergeleitet. Vor allem der Verlauf des Antennensteuerungswinkels, der für die Synchronisation der von den Antennen beleuchteten bzw. empfangenen Bereiche wichtig ist, wird berechnet. Weitere wichtige Parameter sind die Ausdehnung der Szene in Azimut und der Verlauf der Azimut Dopplerverschiebung, die in den Daten auftaucht.

Weil die Berechnung der Antennensteuerungswinkel unter Voraussetzung einer ebenen Geometrie relativ einfach ist, werden einige Parameter angepasst, um diese Berechnungen zu ermöglichen. Dadurch werden Effekte kompensiert, die durch die Erdrotation und die ellipsoide Form der Erde auftauchen.

Der zweite Teil dieser Arbeit zeigt eine Möglichkeit auf, Orbits, die dem Einfluss von Gravitationsstörungen unterliegen, zu verfolgen und zu interpolieren. Dies geschieht mit Hilfe eines Kalman Filters. Dabei werden Positions- und Geschwindigkeitsmessungen mit der Information aus einem Gravitationsmodell fusioniert, um die Genauigkeit, in der die Satellitenpositionen vorliegen, zu erhöhen.

Notation

General Conventions

- Geometrical vectors that are defined by a length and a direction are marked with an arrow: $\vec{x}$

  State vectors or geometrical vectors that represent a row or a column of a matrix are underlined: $\underline{x}$

  This notation represents a column vector. A row vector is the transpose of a column vector.

  The norm or length of a geometrical vector is expressed by omitting the arrow: $|\vec{x}| = x$
- The norm of a vector's derivative and the derivative of a vector's norm are distinguished according to the following example:

$$\vec{x}(t) = \begin{bmatrix} t \\ t+1 \end{bmatrix} ; \left|\vec{x}(t)\right| = x(t) = \sqrt{2 \cdot t^2 + 2 \cdot t + 1}$$

$$\frac{d}{dt}\vec{x}(t) = \dot{\vec{x}}(t) = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad ; \frac{d}{dt}\left|\vec{x}(t)\right| = \dot{x}(t) = \frac{1}{2} \cdot \frac{4 \cdot t + 2}{\sqrt{2 \cdot t^2 + 2 \cdot t + 1}}$$

$$\left|\frac{d}{dt}\vec{x}(t)\right| = \left|\dot{\vec{x}}(t)\right| = \sqrt{2} \neq \frac{d}{dt}\left|\vec{x}(t)\right|$$

- Aside from a few exceptions that are defined when they occur, capital letters represent matrices.

The transpose of a matrix A or a vector $\underline{v}$ is A^T and $\underline{v}^T$ respectively. The inverse of a matrix is A^{-1}.

The scalar product of two vectors is $\vec{v} \cdot \vec{x}$ or $\underline{x}^T \underline{y}$. The cross product of two geometrical vectors is $\vec{v} \times \vec{x}$.

Angles are usually expressed by Greek letters. The Greek letter ω is sometimes assigned to the angular velocity, but also to the angular argument of perigee in orbital mechanics. Both cases are common in literature, so this notation was also chosen for this document. The context will explain the meaning of ω in a particular formula.

Formula Symbols

Geometrical Vectors

$\vec{P}$	Position vector
$\vec{R}$	Slant range vector
$\vec{v}$	Velocity vector
$\vec{g}$	Acceleration vector (In literature, also $\vec{a}$ can often be found. In this work, $\vec{g}$ was chosen because all accelerations that occur are due to gravitational influences. A confusion with the semi major axis a of an ellipse is also avoided by this notation.)
$\vec{e}$	Unit vector (coordinate basis)
$\vec{a}_P$	Antenna pointing unit vector

$\vec{x}$	Point of ellipsoidal intersection
$D_1;D_2;D_3$	Rotation matrices
D	Coordinate transformation matrix

Time and Frequency Domain

$t;f$	Signal time and its corresponding frequency ("fast time")
$\tau;f_\tau$	Azimuth time and its corresponding frequency ("slow time")
$\Delta t;T;t_0\ldots$	Time difference, time constant etc…
$w(t);w(f)$	Window function in time and frequency domain
$\underset{t\to f}{\mathcal{F}}\{s(t)\}=S(f)$	Fourier transform of $s(t)$.

State Space Model

$\underline{\hat{x}}^-$	Predicted state vector
$\underline{\hat{x}}^+$	Filter estimate
$\underline{y}_b$	Measurement vector
$\underline{y}$	Observation vector
A	State transition matrix
C	Observation matrix
P^-	Prediction covariance matrix
P^+	Estimation covariance matrix
Q	Driving noise matrix
R	Measurement noise matrix (not to confuse with the slant range vector!)
K	Kalman Gain
res	residual
H	Linearized observation matrix

Angles

Ψ	Antenna azimuth steering angle
$\eta=\vartheta+roll$	Off-nadir angle (antenna pointing)
ϑ	Angle between antenna pointing vector and z-axis of the satellite system If *roll* = 0° then ϑ corresponds to the off-nadir angle.
$roll$; $pitch$; yaw	Attitude angles
ω	Angular argument of perigee, also: angular velocity of the earth and of a satellite respectively
Ω	Rectascension
i	Inclination
$E(t);M(t);\varphi(t)$	Eccentric, mean and true anomaly in orbital mechanics
Φ	Geographic latitude
δ	Geocentric latitude
Λ	Geographic longitude

Other

λ	Wavelength
c_0	Speed of light
a	Semi major axis

b	Semi minor axis
e	Eccentricity
P_{nm}	Associated Legendre functions
h	Altitude, height
B	B-Parameter, SAR related
PRF	Pulse repetition frequency
PCA	Point of closest approach
Tx	Transmitter
Rx	Receiver